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Low Temperature Photoluminescence and Leakage Current Characteristics of InAs-GaSb Superlattice Photodiodes

by P.A. Folkes, J. Little, S. Svensson, and K. Olver

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14. ABSTRACT
We report the results of a study of the temperature-dependent photoluminescence (PL) and leakage current characteristics of a set of type II indium arsenide (InAs)-gallium antimonide (GaSb) superlattice (SL) photodiode structures. We find that the PL efficiency of high-quality structures is determined by Shockley-Read and trap-assisted tunneling nonradiative recombination processes. Our results suggest a possible correlation between trap-assisted tunneling in some SL structures and an anomalous decrease in the PL efficiency with increasing temperature over the range 40–78 K, and provide insight into the effect of defects and SL homogeneity on the PL and transport characteristics of the photodiodes.

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Summary

We report the results of a study of the temperature-dependent photoluminescence (PL) and leakage current characteristics of a set of type II indium arsenide (InAs)-gallium antimonide (GaSb) superlattice (SL) photodiode structures. We find that the PL efficiency of high-quality structures is determined by Shockley-Read and trap-assisted tunneling nonradiative recombination processes. Our results suggest a possible correlation between trap-assisted tunneling in some structures and an anomalous decrease in the PL efficiency with increasing temperature over the range 40–78 K. We recommend further studies to confirm these results and provide further insight into the effect of defects and SL homogeneity on the PL and transport characteristics of the photodiodes.

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1. Introduction

Strong interest in the development of high-performance infrared (IR) detectors led to proposals for the use of type II indium arsenide (InAs)-gallium antimonide (GaSb) (*1*) and InAs-gallium indium antimonide (GaInSb) (*2*) superlattices (SLs) for IR detection. The InAs-GaSb SL is composed of thin alternating InAs and GaSb layers that utilize quantum confinement to vary its bandgap by varying the SL periodicity, while the strained InAs-GaInSb SL employs quantum confinement and strain effects to vary its bandgap and optical characteristics. Intensive research over the past two decades has led to significant progress (*3–8*) in understanding the characteristics of type II SL photodiodes. However, type II SL photodetectors have not realized their predicted performance (*2*, *9*) expectations, which are based on the intrinsic characteristics of type II GaSb/InAs SLs.

As a result of the type II band lineup in InAs-GaSb SL, where the InAs conduction band is lower in energy than the top of the GaSb valence band, photoexcited carriers are confined in different layers. Electrons are mostly confined in the InAs layers while holes are primarily confined in the GaSb layers; consequently, there is a decrease in the electron-hole wavefunction overlap and the strength of the optical transitions between InAs-GaSb SL conduction and valence subbands (*10*). Theory (*10*) predicts that the integrated photoluminescence (PL) intensity from InAs-GaSb SLs with a fixed InAs width is inversely proportional to the width of the GaSb layer; however, experimental results show a strong decrease in PL intensity from the InAs-GaSb SL with decreasing GaSb width (*11*) due to extrinsic effects. Type II SL materials have a high density of efficient Shockley-Read (S-R) nonradiative recombination centers, which significantly reduce their PL efficiency (*12,13*). Trap-assisted tunneling increases the leakage current and limits the performance of InAs/GaSb SL photodiodes (*14,15*); however, it is not known if there is any correlation between trap-assisted tunneling and the PL characteristics of type II photodiodes.

In this report, we present the results of a study of the temperature-dependent PL and leakage current characteristics of a set of InAs-GaSb SL photodiodes. We find that the PL efficiency of high-quality structures is determined by S-R and trap-assisted tunneling nonradiative recombination processes. Our results suggest a possible correlation between defect-assisted tunneling in high-quality SL structures and an anomalous decrease in the PL efficiency with increasing temperature and provide insight into the effect of defects and SL homogeneity on the PL and transport characteristics of type II SL photodiodes.

2. Experiment

Experiments were carried out on three different InAs/GaSb photodiode structures that were grown under slightly different growth conditions and exhibited different temperature-dependent PL characteristics over the range 11–120 K. The photodiode structure comprises the following layers: p-GaSb substrate, 5000 Å p-GaSb buffer, 50 periods of undoped GaSb/InAs SL, and 350 Å n-InAs with a Si doping of 2×10^{18} cm^{-3}. Structure A has a 75 Å GaSb/24 Å InAs SL, structure B has a 100 Å GaSb/24 Å InAs SL, and structure C has a 100 Å GaSb/22.5 Å InAs SL.

The samples were mounted on the cold finger of a closed-cycle cryostat and excited with a 980 nm laser with excitation intensities up to 64 W/cm^2. The PL measurements were carried out as a function of temperature over the range 11–120 K using a Nicolet Fourier Transform Infrared (FTIR) spectrometer to detect the luminescence. Photodiodes with a 250 µm diameter mesa, a ring Ohmic contact to the n-InAs layer, and an Ohmic contact to the substrate were fabricated from these structures and used for measurements of the photodiode leakage current at an applied reverse voltage of 0.01 V over the range 11–120 K.

3. Results and Discussion

Figure 1 shows the 11 K PL intensity as a function of wavelength from the three structures using an excitation intensity of 64 W/cm^2. There are clear differences in the PL efficiency and linewidth of the samples. Structure C exhibits an integrated PL intensity, which is a factor of 6.7 larger than the integrated PL from structure B and a full-width-at-half-maximum (FWHM) linewidth of 24 meV compared to 65 meV for structure B. Structure A has a PL linewidth of 40 meV and an integrated PL intensity, which is a factor of 2.9 smaller than that of structure C. The observed PL band edge energy of 0.35 eV for structure C agrees with previous measurements (*11,16*) and theory (*16*). This data in conjunction with its strong PL efficiency provides evidence of structure C's quality. In contrast, structure B's weak PL efficiency, its extremely broad PL linewidth, and the fact that its measured band edge energy of 0.31 eV is significantly lower than theoretical prediction (*11*) suggest that its SL structure is nonuniform and has significant interface roughness (*17*). The 11 K PL spectra of structure C at various excitation intensities is plotted in figure 2. The data show that as the excitation intensity is increased from 16 W/cm^2 to 64 W/cm^2, there is a slight blue-shift in the PL peak energy and high-energy broadening of the PL spectra, which is indicative of laser-induced sample heating (*13*) for excitation intensities greater than 16 W/cm^2.

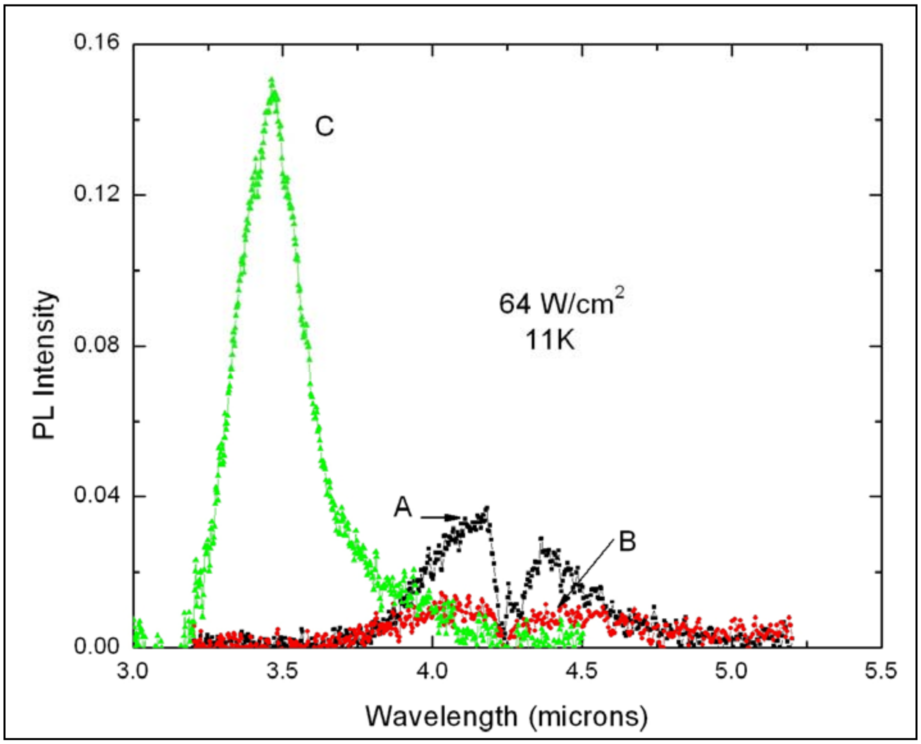

Figure 1. The 11 K PL spectra of structures A, B, and C.

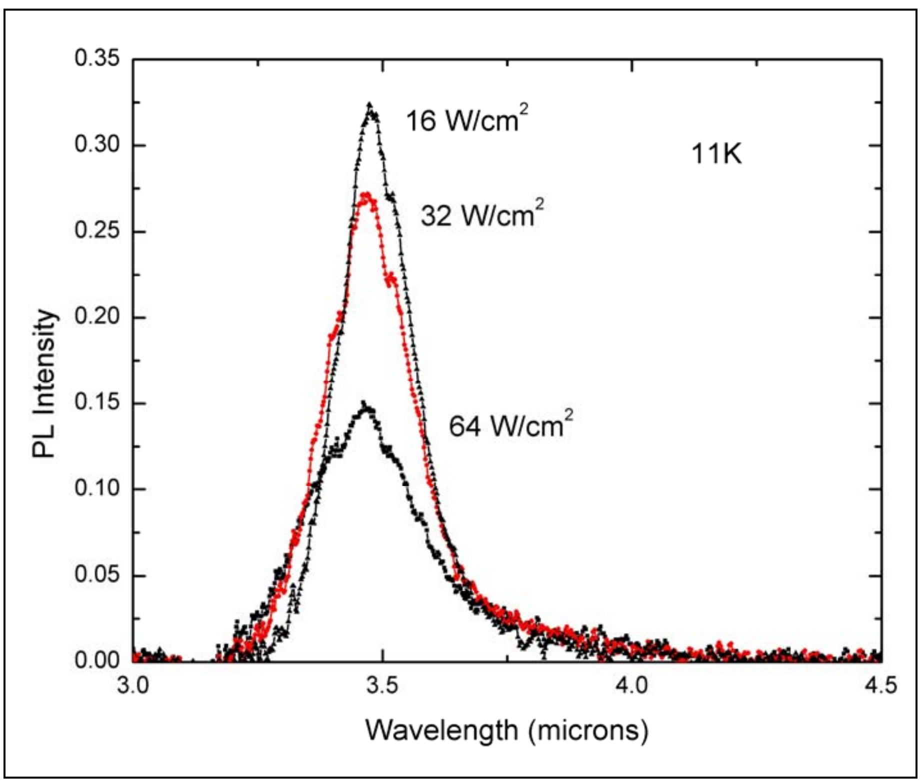

Figure 2. The 11 K PL spectra of structure C at various excitation intensities.

Figure 3 shows that the PL from structure C over the 11–20 K range with an excitation intensity of 16 W/cm^2 shows features that are 8 meV and 4 meV above and below the PL peak at .35 eV, respectively. Bandstructure theory (*10*, *16*, *18*) suggests that the observed PL features can be attributed to transitions from the lowest conduction subband to the three highest valence subbands. The observation of these PL transitions, which are predicted to have significant oscillator strength due to strong valence band mixing in the GaSb/InAs SL (*10,18*), provides further proof of sample C's quality. The theory also predicts an increase in the hole mobility along the SL growth direction as a result of valence band mixing with the light hole subband with the highest energy.

The integrated PL intensity observed from structure C with an excitation intensity of 16 W/cm^2 decreases as the sample temperature is increased, as shown in figures 3 and 4. Figure 4 also shows that for sample temperatures below 40 K and an excitation intensity of 64 W/cm^2, we observe a decrease in the integrated PL intensity due to a laser-induced increase in carrier temperature. The three structures exhibit approximately the same proportional decrease in integrated PL intensity as substrate temperature is increased from 11 K to 40 K, as shown in figure 5. Over the range 40–78 K, structures A and B exhibit roughly the same decrease while structure C exhibits an anomalously fast decrease in integrated PL intensity. Surprisingly, at temperatures above 78 K, we do not observe any PL from structure C, while we observe weak PL from structures A and B.

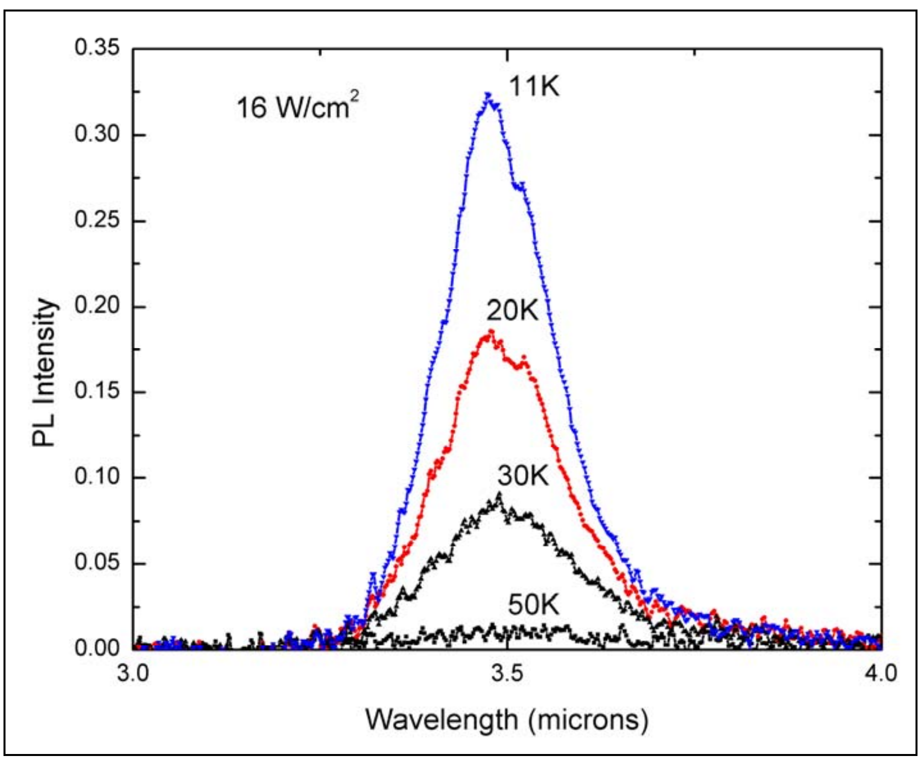

Figure 3. PL spectra of structure C at various temperatures.

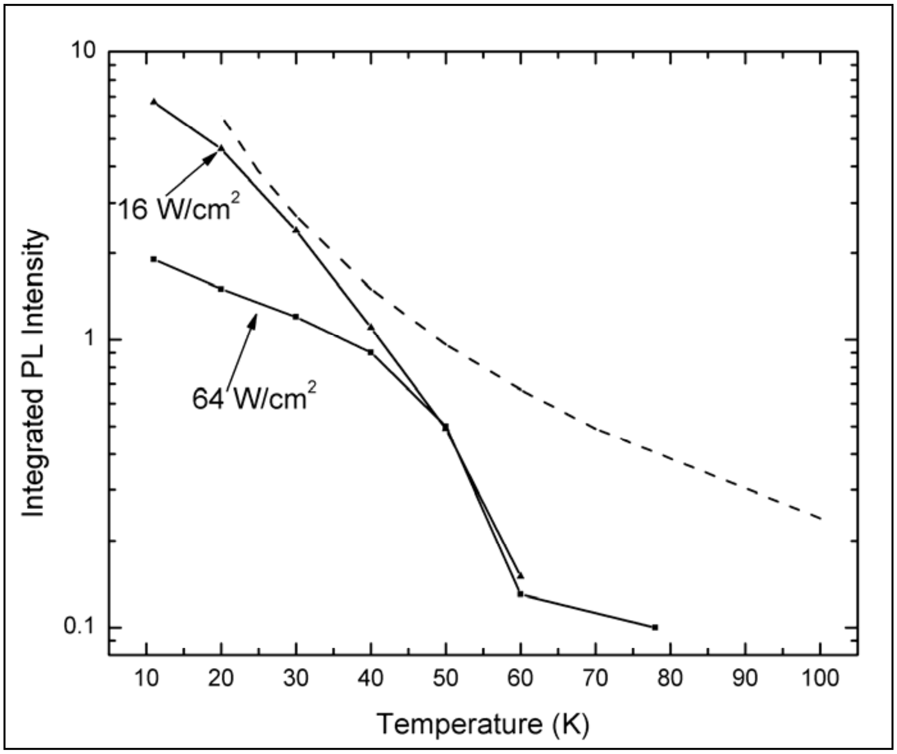

Figure 4. Temperature dependence of structure C's integrated PL intensity.

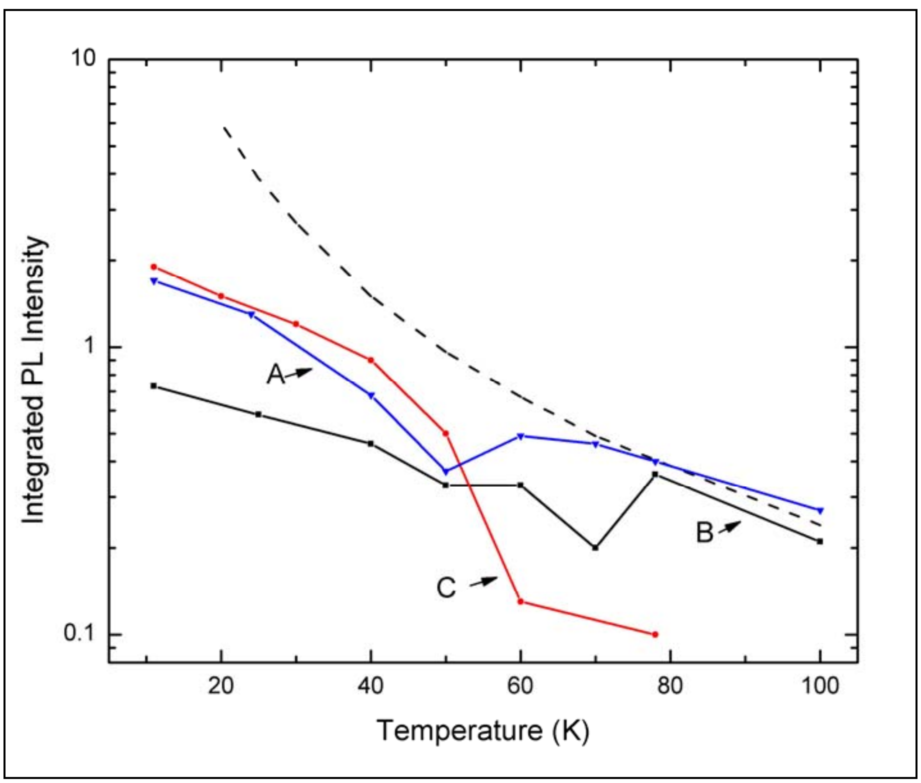

Figure 5. Temperature dependence of the integrated PL intensity of structure A, B, and C; the dashed line indicates the T^{-2} dependence.

The integrated PL intensity is proportional to the PL efficiency ~ τ / τ_r , where τ is the net minority carrier lifetime and τ_r is the (spontaneous emission) radiative recombination lifetime. The net minority carrier (hole) lifetime in GaSb/InAs SLs is dominated by nonradiative recombination at high-density S-R centers (*12*) over a wide range of temperature, T. It can be shown that the PL efficiency has an approximate T^{-2} dependence if τ is dominated by nonradiative S-R recombination (*13*). At temperatures lower than some limit, which is determined by the density of S-R centers and the SL electron density, the radiative recombination lifetime will become dominant and the integrated PL intensity will be nearly independent of temperature. Figure 4 shows that structure C exhibits roughly a T^{-2} dependence over the range 20–40 K, when an excitation intensity of 16 W/cm^2 is used. The deviation from the T^{-2} dependence for T < 20 K suggests that radiative recombination dominates the net carrier lifetime in this temperature range. The observed change in the slope of structure C's PL intensity, for T < 40 K with an excitation intensity of 64 W/cm^2, could be attributed to carrier heating. Figure 5 shows that over the range 40 K < T < 100 K, the integrated PL intensity from structures A and B decrease with roughly a T^{-2} temperature dependence while the integrated PL intensity from structure C exhibits an anomalously fast decrease with increasing temperature. The data suggests that the anomalous decrease in the integrated PL intensity of structure C is caused by the combination of S-R recombination and another nonradiative recombination process.

Leakage current measurements of a representative set of photodiodes as a function of temperature are shown in figures 6 and 7. All three structures exhibit a large variation in the 11 K diode leakage current. Note that the leakage current of diodes from structures C and A is less sensitive to increasing temperature than that of structure B diodes. As shown in figures 6 and 7, the leakage current of diodes from structures C and A increases by a factor, which is typically less than 2 as temperature is increased from 40 K to 80 K, indicating that the dominant leakage current mechanism over this temperature range in structures C and A is trap-assisted tunneling (*14, 15*) at the p-GaSb/n-SL interface. In contrast, the leakage current of structure B diodes increases by an average factor of around 30 as the temperature is increased from 40 K to 80 K, indicating that the dominant leakage current mechanism in this structure is the generation-recombination leakage current generated by S-R defects in the SL depletion region (*14, 15*). This data suggests that structures C and A have a higher density of the interface traps, which are responsible for trap-assisted tunneling than structure B.

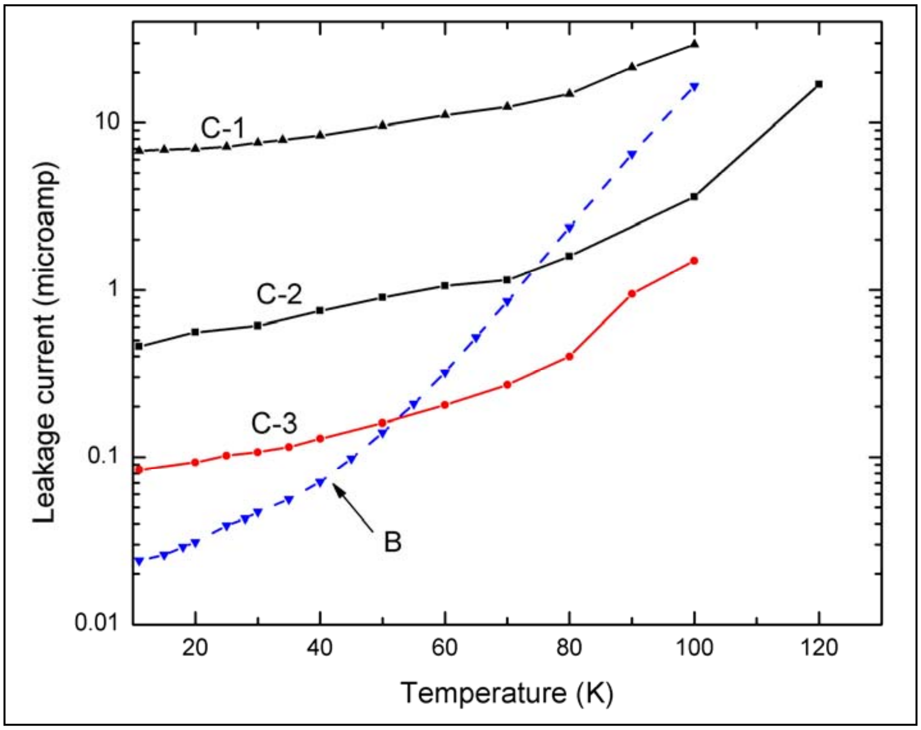

Figure 6. Temperature dependence of the leakage current of several photodiodes from structure C and a photodiode from structure B.

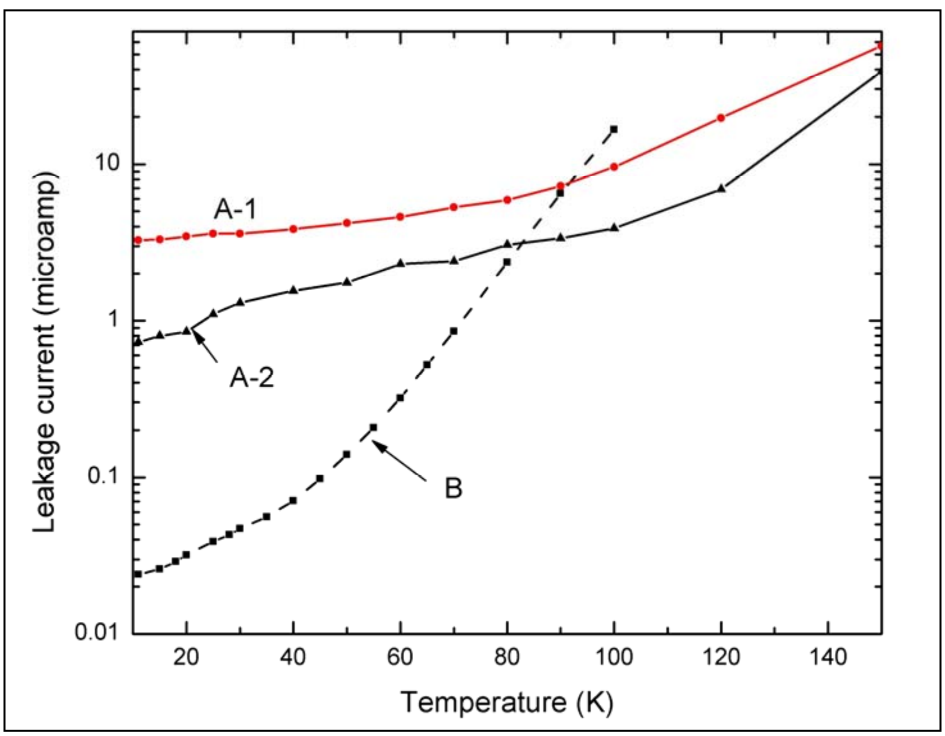

Figure 7. Temperature dependence of the leakage current of photodiodes from structures A and B.

Note that photoexcited holes in the SL region will undergo drift/diffusion to the p-GaSb/n-SL interface where trap-assisted tunneling of electrons from the GaSb valence band into holes at the interface enhances the transport of holes across the p-GaSb /n-SL interface (*7*). Structure C's quality and the associated strong valence band mixing suggest that it has a larger hole mobility over the range 40–80 K than the other structures. The large hole mobility combined with trap-assisted tunneling at the p-GaSb/n-SL interface results in the fast removal of photoexcited holes from the SL and the anomalous fast decrease in the PL efficiency because this mechanism enhances the decrease in PL efficiency caused by S-R recombination. This model is supported by the fact that structure A exhibits trap-assisted tunneling but not the anomalous fast decrease in the integrated PL intensity with increasing temperature. This is consistent with the assumption that structure A has a smaller hole mobility (based on its larger PL linewidth) than structure C and a slower transport of photoexcited holes to the p-GaSb/n-SL interface.

4. Conclusion

The temperature-dependent PL and leakage current characteristics of a set of type II InAs-GaSb SL photodiode structures have been studied over the temperature range 11–120 K. We find that the PL efficiency of some structures is determined by S-R and trap-assisted tunneling nonradiative recombination processes. Our results suggest a possible correlation between trap-assisted tunneling in some SL structures and an anomalous decrease in the PL efficiency with increasing temperature over the range 40–78 K, and provide insight into the effect of defects and SL homogeneity on the PL and transport characteristics of the photodiodes.

References

1. Sal-Halasz, G. A.; Tsu, R.; Esaki, L. *Appl. Phys. Lett.* **1977**, *30*. 651.
2. Smith, D. L.; C. Mailhiot, C. *J. Appl. Phys.* **1987**, *62*, 2545.
3. Miles, R. H.; Chow, D. H.; Hamilton, W. J. *J. Appl. Phys.* **1991**, *71*, 211.
4. Arch, D. K.; Wicks, G.; Tonaue, T.; Staudenmann, J-L. *J. Appl. Phys.* **1985**, *58*, 3933.
5. Youndale, E. R.; Meyer, J. R.; Hoffman, C. A.; Bartoli, F. J.; Grein, C. H.; Young, P. M.; Ehrenreich, H.; Miles, R. H.; Chow, D. H. *Appl. Phys. Lett.* **1994**, *64*, 3160.
6. Fuchs, F.; Weimer, U.; Pletschen, W.; Schmitz, J.; Ahlswede, E.; Walther, M.; Wagner, J.; Koidl, P. *Appl Fhys. Lett.* **1997**, *71*, 3251.
7. Johnson, J. L.; Samoska, L. A,; Gossard, A. C.; Merz, J. L.; Jack, M. D.; Chapmna, G. R.; Baumgratz, B. A.; Kosai, K.; Johnson, S. M. *J. Appl. Phys.* **1996**, *80*, 1116.
8. Hood, A.; Hoffman, D.; Wei, Y.; Fuchs, F.; Razeghi, M. *Appl. Phys. Lett.* **2006**, *88*, 062112.
9. Grein, C. H.; Young, P. M.; Ehenreich, H. *J. App. Phys.* **1994**, *76,* 1940.
10. Chang, Y.-C; Schulman, J. N. *Phys. Rev. B 31* **1985,** 2069.
11. Ongstad,, A. P.; Kaspi, R.; Moeller, C. E.; Tilton, M. L.; Gianardi, D. M.; Chavex, J. R.; Dente, G. C.. *J Appl. Phys.* **2001**, *89*, 2185.
12. Miles, R. H.; Chow, D. H.; Zhang, Y.-H.; Brewer, P. D.; Wilson, R. G., *Appl. P hys. Lett.* **1995,** *66*, 1921.
13. Canedy, C. L.; Brewley, W. W.; Kim, C. S.; Kim, M.; Vurgaftman, I.; Meyers J. *J ApplePhyes*, **2003**, *94*, 1347.
14. Yang, Q. K.; Fuchs, F.; Schmitz, J.; Pletschen, W. *Apple Phys. Lett.*, **2002**, *81*, 475.
15. Prineas, J. P.; Mairov, M.; Cao, C.; Olesberg,, J. T.; Flatt, M. E.; Raddy, M.; Coretsopoulos C.; Itzler, M. *Prob. SPIE 6119* **2006**, SPIE 6119, 611904.
16. Kaspi, R.; Moeller, C.; Ongstad, A.; Thilton, M. L.; Gianardi, D.; Dente, G.; Gopaladasu, P. *Appy. Phys. Lett.* **2000**, *76*. 409.
17. Ongstad, A. P.;Dente G. C.; Tilton, M. J.;Gianardi, D.; Turner, G. *J. Appl. Phys..* **2000**, *87,* 7896.

18. Schulman, J. N.; Chang, Y.-C. *Phys. Rev. B* **1985** *31*, 2056.

Acronyms

FWHM	full-width-at-half-maximum
GaInSb	gallium indium antimonide
GaSb	gallium antimonide
InAs	indium arsenide
IR	infrared
PL	photoluminescence
SLs	superlattices
S-R	Shockley-Read

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